Muon Collider

Daniel Schulte for the Muon Collider Collaboration

Why Again Muon Collider?

Most of the muon collider R&D has been done by MAP in the US

- Experimental programme at MICE in the UK
- alternative LEMMA concept considered mainly at INFN
- Still the basis for our designs

Interest in Europe started with last Strategy Update

- **Change of goals**: Started looking for very high energy high-luminosity lepton collider
  - The champion is CLIC at 3 TeV, which has been optimised over decades for this
    - 18 GCHF, 590 MW power consumption
  - The muon collider promises to be able to go to 10 TeV or higher
- **Technology and design advances** since MAP
  - e.g. superconducting magnet technology (HTS)
  - e.g. rectilinear cooling channel
  - Progress on specific technologies for the muon collider
  - Expect competitive cost and power consumption

CERN allocated budget to muon collider and initiated collaboration

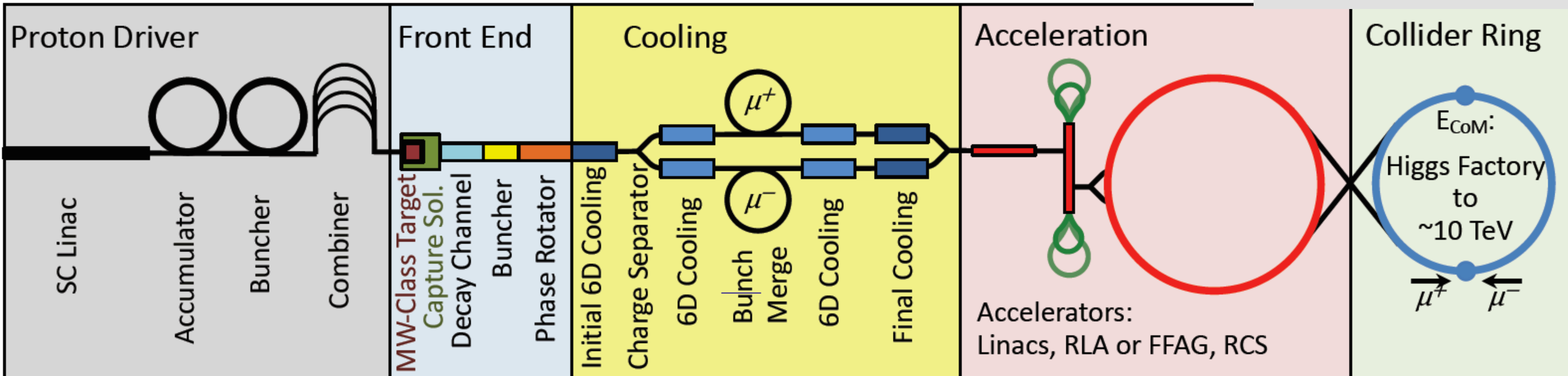
Muon collider is part of European Accelerator R&D Roadmap

- evaluated in detail, with **lots of help from US experts**

Proton-driven Muon Collider Concept

Muon collider design is driven by finite muon lifetime

MAP collaboration



Short, intense proton bunches to produce hadronic showers

Muon are captured, bunched and then cooled by ionisation cooling in matter

Collision

Acceleration to collision energy

Protons produce pions
Pions decay to muons

Muon Collider Opportunity

CLIC is highest energy proposal with CDR

- at the limit of what one can do (decades of R&D)
- No obvious way to improve

Cost 18 GCHF, power 590 MW

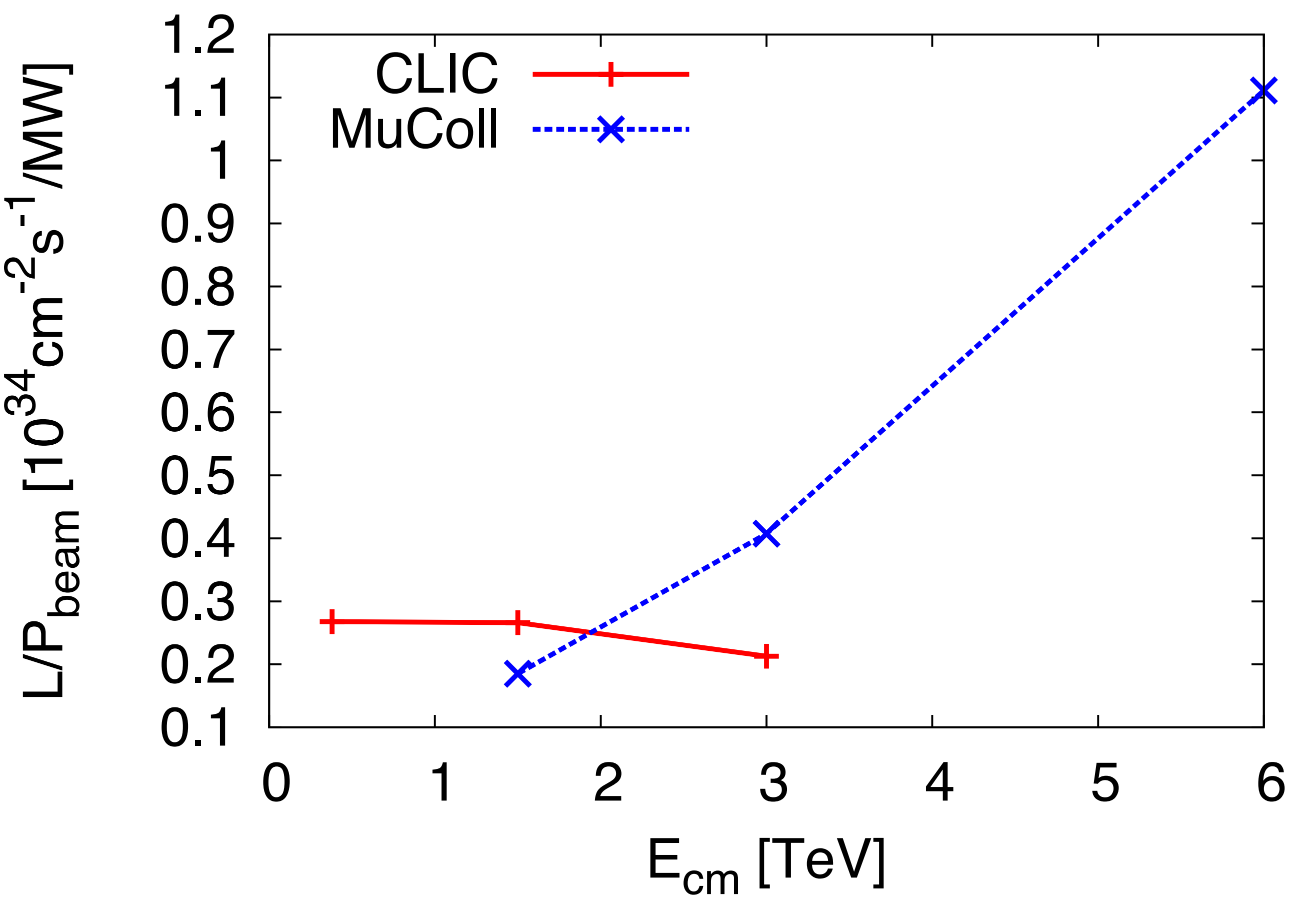
Muon Collider:

Acceleration and collision in multiple turns in rings promises

- **Power efficiency**
- **Compact tunnels**
  - 10 TeV similar to 3 TeV CLIC
- **Cost effectiveness**
- **Natural staging** is natural

Synergies exist (neutrino/higgs

Detailed studies needed for quantitative statements



Muon collider promises unique opportunity for a **high-energy, high-luminosity lepton collider**

Luminosity Goals

Target integrated luminosities

$\sqrt{s}$	$\int \mathcal{L}dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

Note: currently consider 3 TeV and either 10 or 14 TeV

- Tentative parameters achieve goal in 5 years
- FCC-hh to operate for 25 years
- Might integrate some margins
- Aim to have two detectors

Feasiblity addressed

- will evaluate luminosity performance, cost and power consumption

Tentative target parameters
Scaled from MAP parameters

Comparison:
CLIC at 3 TeV: 28 MW

Parameter	Unit	3 TeV	10 TeV	14 TeV
L	10^{34} cm^{-2}s^{-1}	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	µm	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	0.63

Key Challenge Areas

10+ TeV is uncharted territory

Identified the key challenges:

- **Physics potential** evaluation, including d**etector concept and technologies**

⇒ Nathaniel

⇒ Donatalla

- Impact on the environment
  - The **neutrino flux mitigation** and its impact on the site (first concept exists)

- The impact of **machine induced background** on the detector, as it might limit the physics reach.

- **High-energy systems** after the cooling (acceleration, collision, …)
  - This can limit the energy reach via cost, power, technical risk and beam quality

- **High-quality muon beam production**
  - MAP study provided design concepts that can deliver high-energy physics programme
  - First experimental verification in MICE
  - Need to optimise and prepare **cooling string demonstration**

Neutrino Flux

International MUON Collider Collaboration

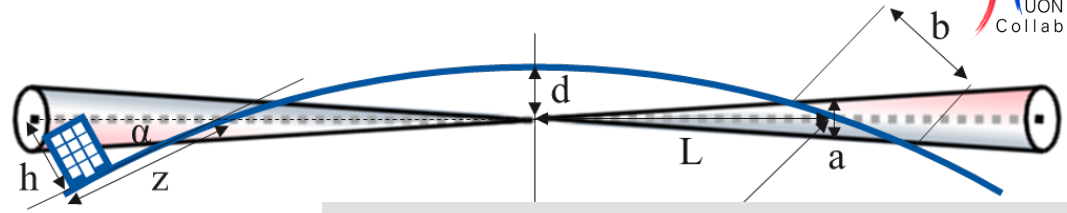
Team of RP experts, civil engineers, beam physicist and FLUKA experts

Goal to be **similar to LHC**: i.e**. negligible**, “fully optimised” (10 x better than MAP goal, 100 x better than legal requirements)

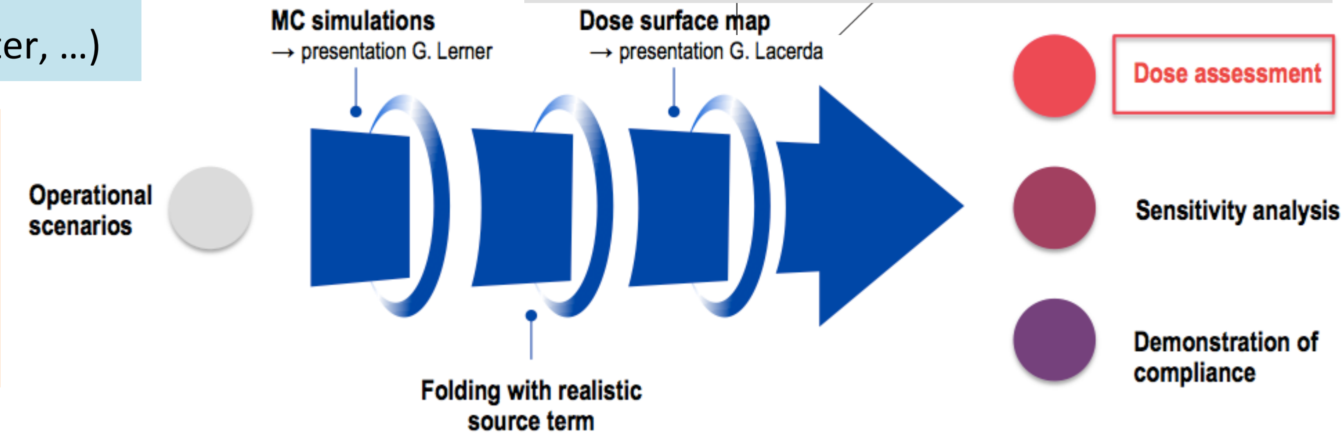
- With indirect effects (air, ground water, …)

Addressed by:
Site choice in direction of experiments
- tools in preparation

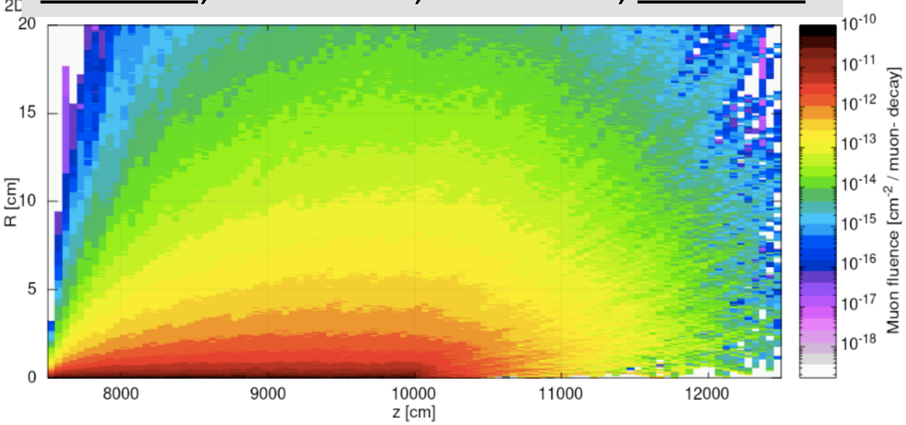
Mechanical mover system in arcs
- allows 14 TeV in 200 m deep tunnel



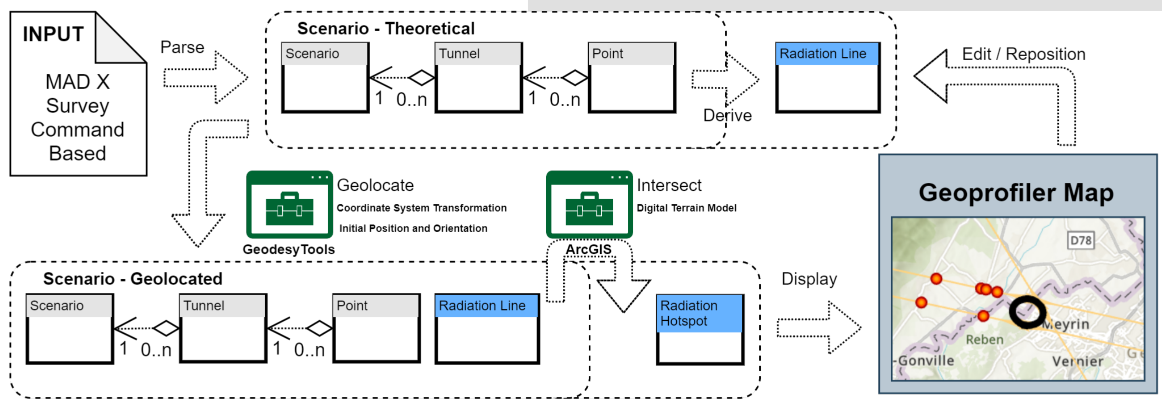
C. Ahdida, P. Vojtyla, M. Widorski, H. Vincke



G. Lerner, D. Calzolari, A. Lechner, C. Ahdida

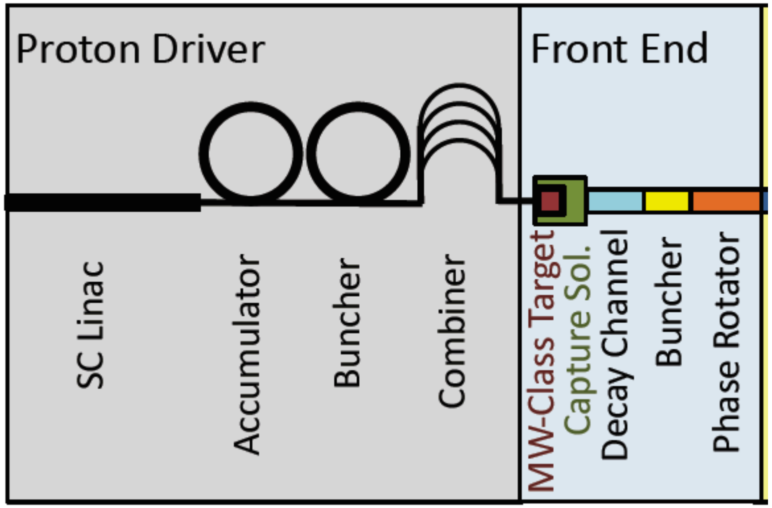


G. Lacerda, Y. Robert, N. Guilhaudin



Mover system and impact on beam will be addressed in the coming years before end if 2025

Proton Complex and Target Area

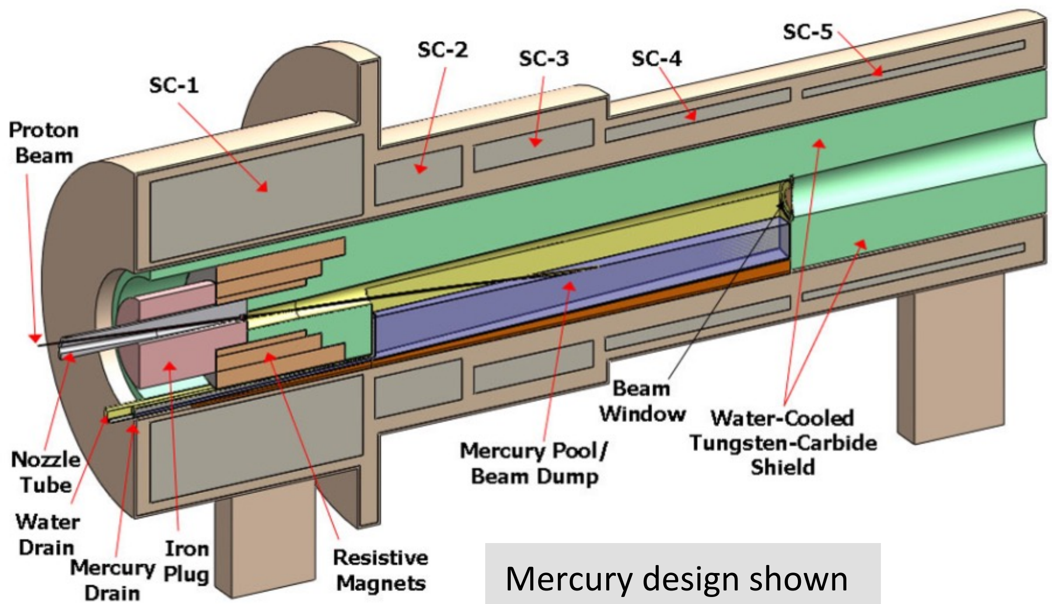


2 MW Proton beam power is no issue some look required at **H- source** and **accumulator and combiner complex**

O(15 T) large aperture superconducting solenoid with shielding and resistive insert

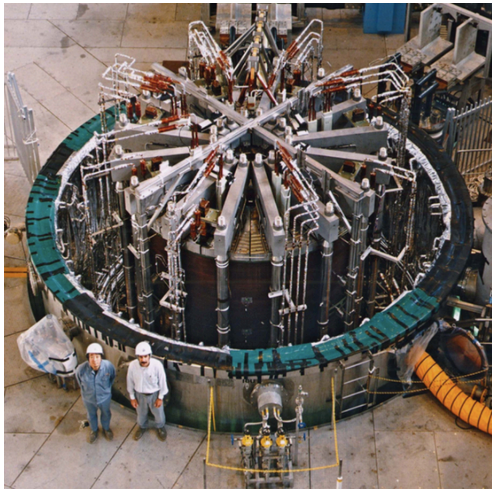
2 MW proton beam target

- liquid mercury demonstrated (MERIT) but safety concerns
- experts think graphite target is possible
- alternatives are considered, e.g. fluidized tungsten, (liquid gallium in the US?), …

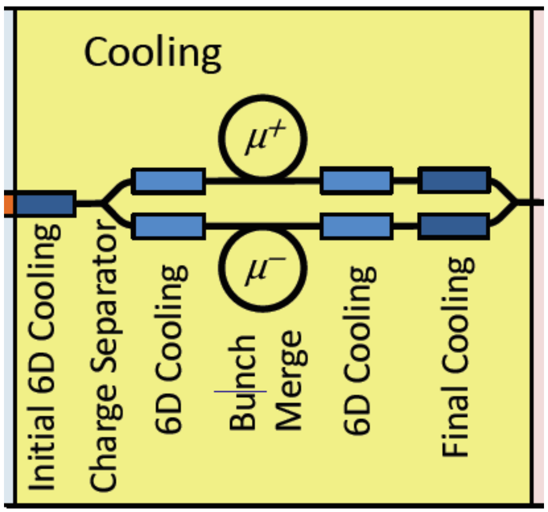


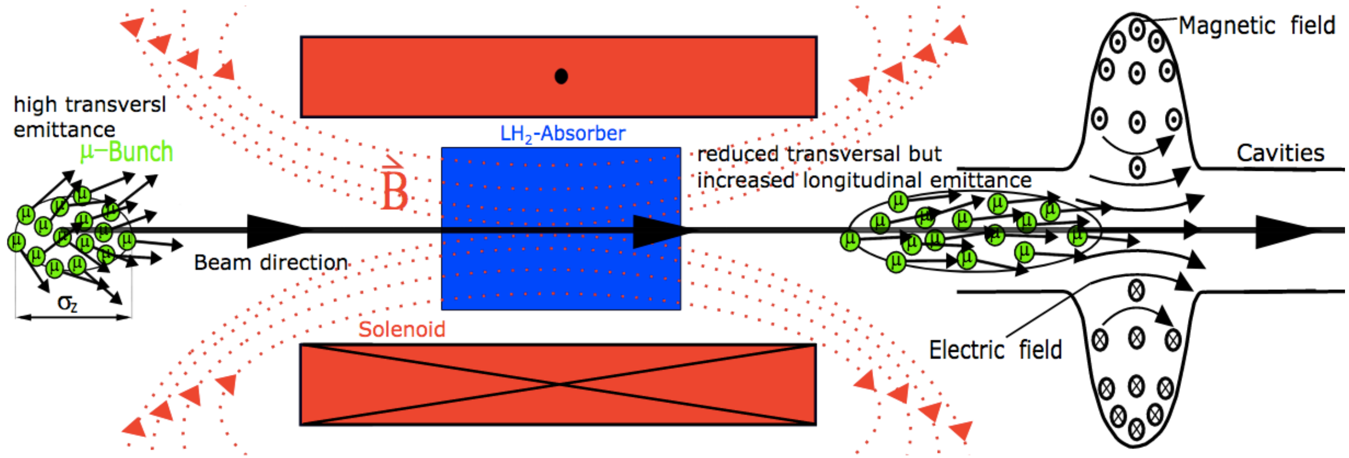
Mercury design shown

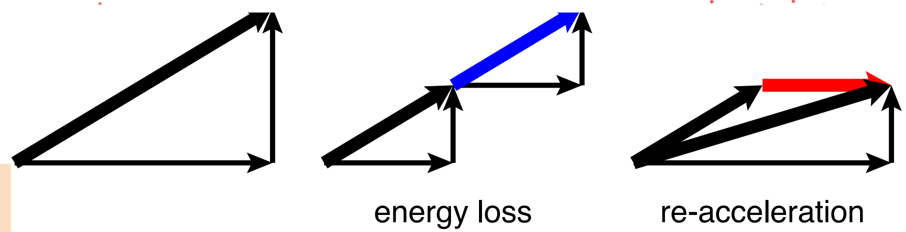
ITER Central Solenoid Model Coil 13 T in 1.7 m (LTS)



Cooling Concept

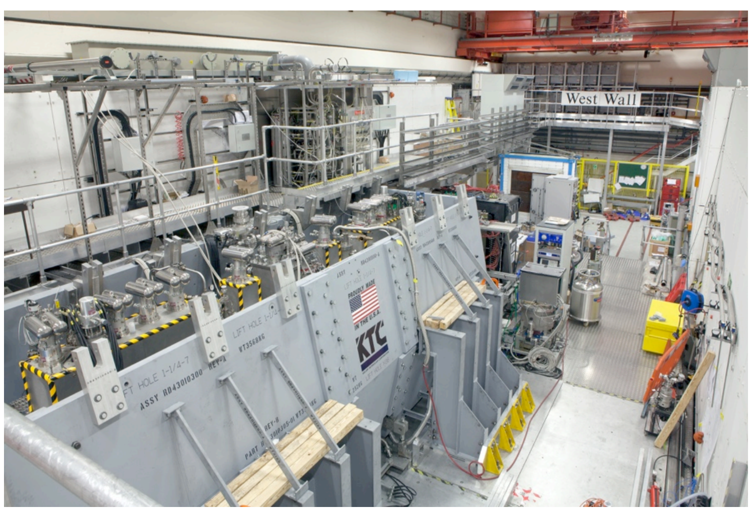




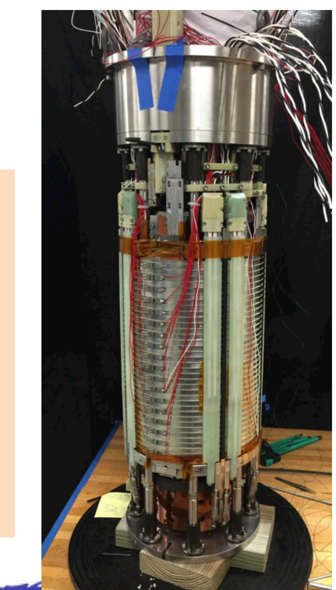


Principle has been demonstrated

MICE (UK) Muon cooling principle

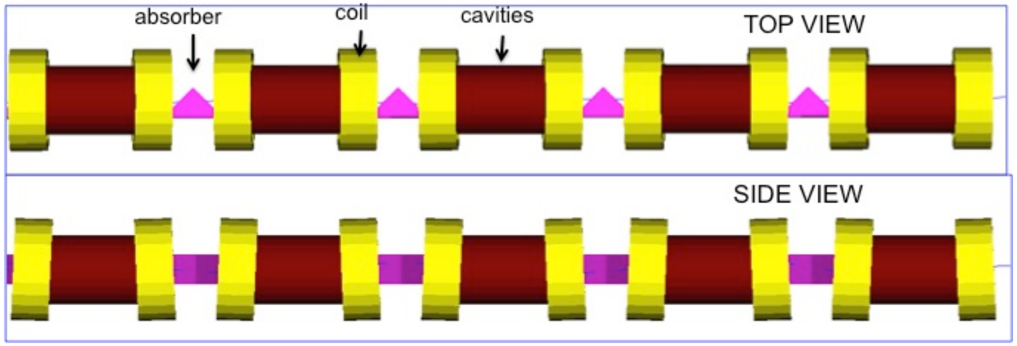


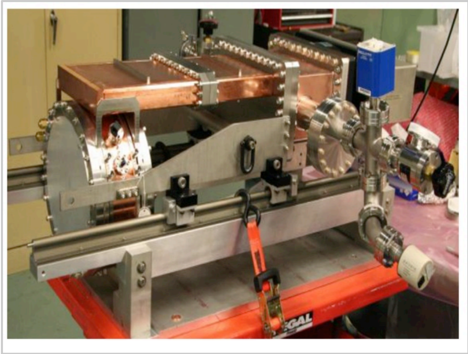
NHFML
32 T solenoid
with HTS



For final cooling **highest-field solenoids** minimise beta-function and impact of multiple scattering
32 T reached with sufficient aperture,
40+ T magnet is being designed
even 50+ T appears possible

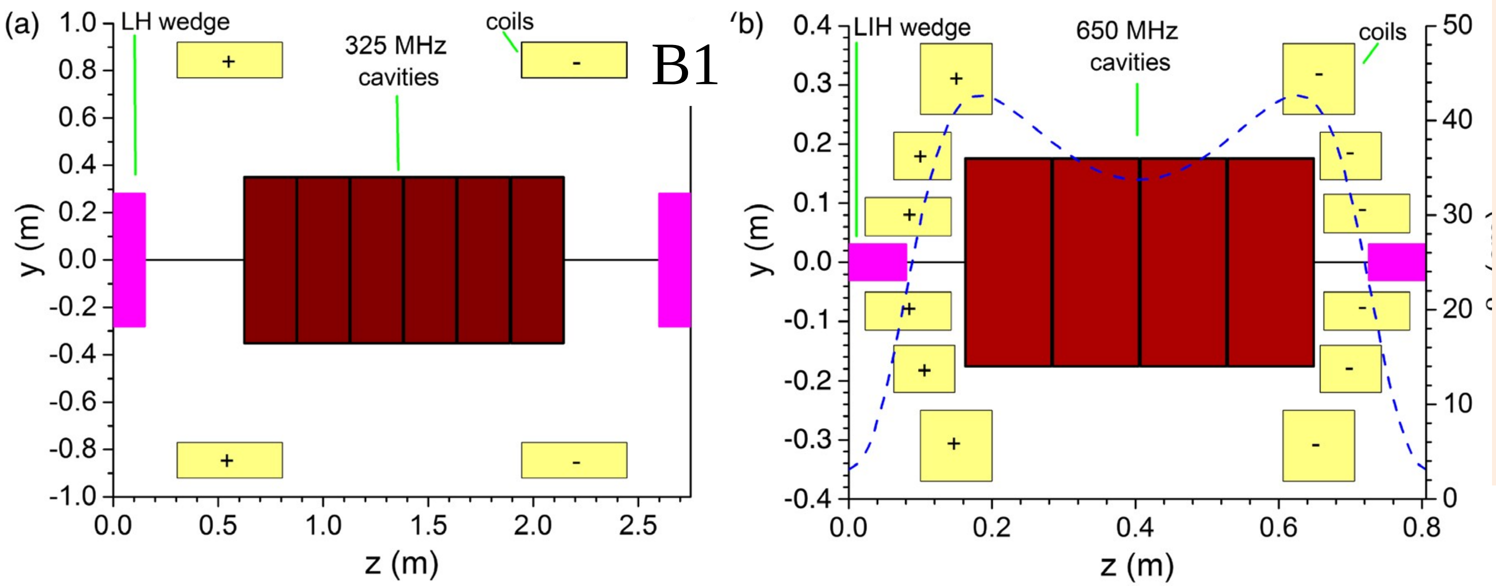
Cooling Cell Design





MuCool: >50 MV/m in 5 T
Two solutions

- H2-filled copper cavities
- Cavities with Be end caps



High-gradient cavities in high magnetic field tests much better than design values but need to develop

Design can achieve target emittance

Will aim for further optimisation
This is the **unique** and **novel** system of the muon collider
Will need a **test facility**

High-energy Acceleration

Rapid cycling synchrotrons (RCS)
- Combine static and ramping magnets

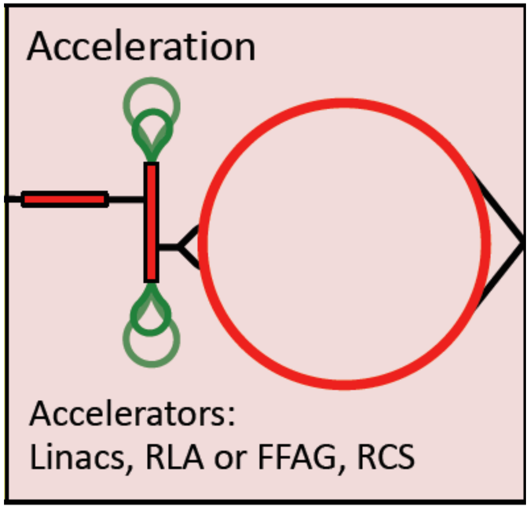
- **Fast-ramping magnets** to follow beam energy
  - normal conducting or novel HTS
  - O(kT/s) required

- Main challenge is **cost and efficiency of magnets and power converters**
  - O(95%) energy recovery

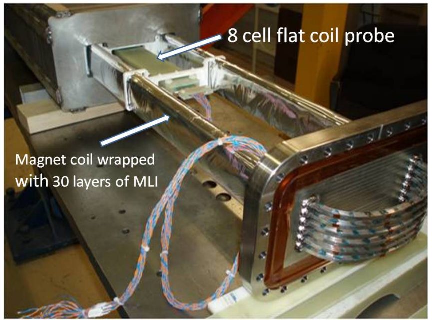
RF system
- **Important single-bunch beam loading**
- 2 x 10 ^{12} particles in O(mm)-long bunch at 5 TeV

Alternative *FFA*
- Fixed (high-field) magnets but large energy acceptance
- Challenging **lattice design** for large bandwidth and limited cost
- **Complex high-field magnets**
- Challenging beam dynamics

FNAL 290 T/s HTS magnet

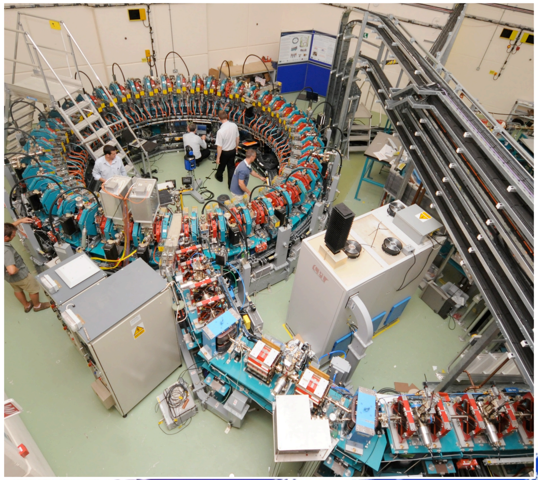


Test of **fast-ramping normal-conducting magnet** design



EMMA proof of FFA principle

Nature Physics 8, 243–247 (2012)



Collider Ring

Beam loss protection O(500 W/m)
- requires larger aperture for shielding
- will be optimised

Indicative simulations of 30 mm W shielding for 10 years:
- suppresses neutrons very well: DPA O(10^{-4})
- 30-40 MGy (3, 10 TeV), very local can be reduced by slightly increased shielding

⇒ taken care of

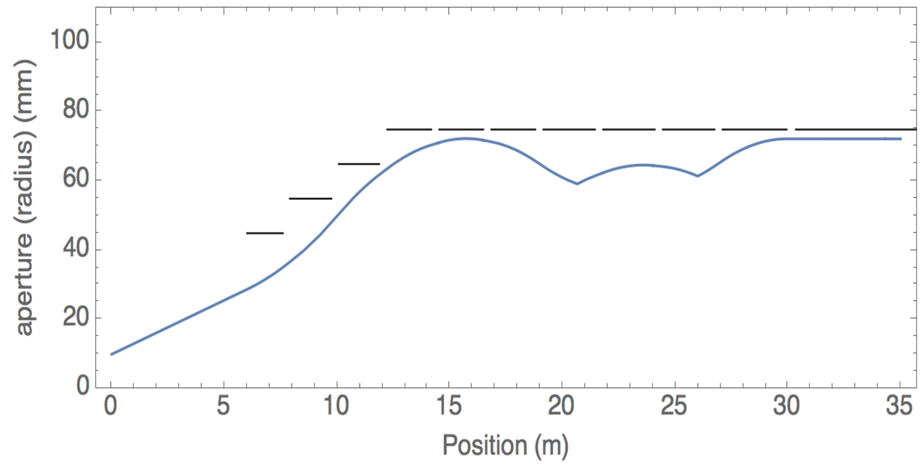
Arc dipoles
in baseline aim for highest field, stress limited

3 TeV:
- 3 km of 11 T Nb_3Sn dipoles (HL-LHC level)

10 TeV:
- 7 km of 16 T dipoles (FCC-hh level)
  - new stress-managed Nb_3Sn
  - or HTS is an option

Acceptable performance with **NbTi**
- but remember luminosity proportional to field

3 TeV FFS Design (MAP)



Parameter	Q1	Q1	Q3	Q4
Aperture (mm)	90	110	130	150
Gradients (T/m)	267	218	-154	-133.5
Peak field (T)	12	12	10+	10+
Dipole field (T)	0	0	2.00	2.00

IP magnets
3 TeV: Field level comparable to HL-LHC (12 vs 11 T), similar aperture
10+ TeV: Higher field and aperture are required,
- consider HTS

Demonstrator Facility

Planning demonstrator facility with muon production target and cooling stations

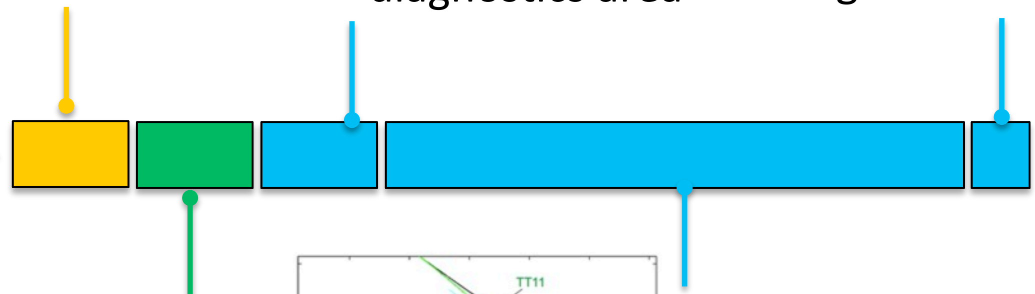
Suitable site on CERN land exists that can use existing proton infrastructure

Other sites should be explored (FNAL?)

Target
+ horn (1st phase) /
+ superconducting solenoid (2nd phase)

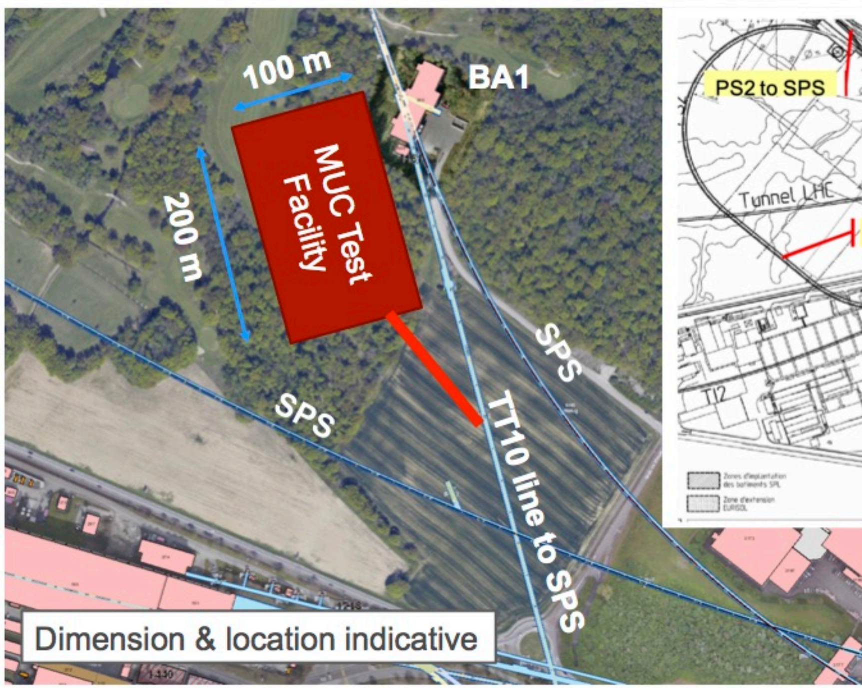
Collimation and upstream diagnostics area

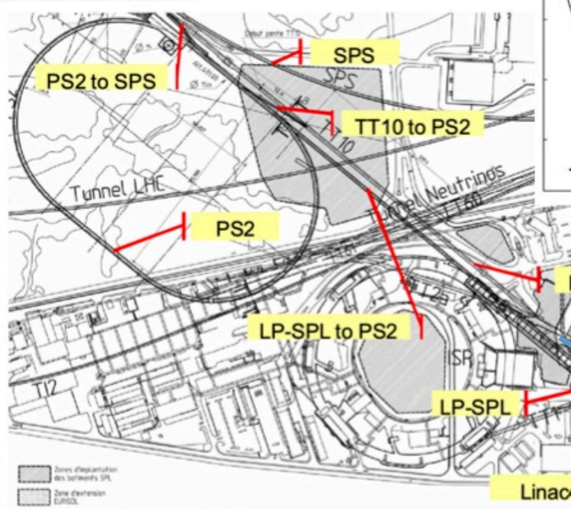
Downstream diagnostics area

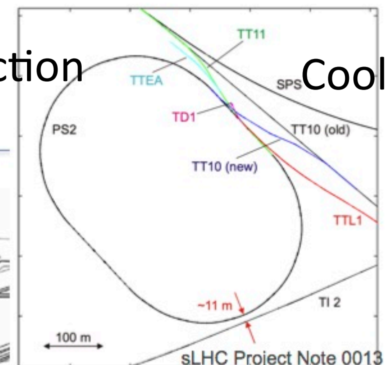


Momentum selection chicane

Cooling area

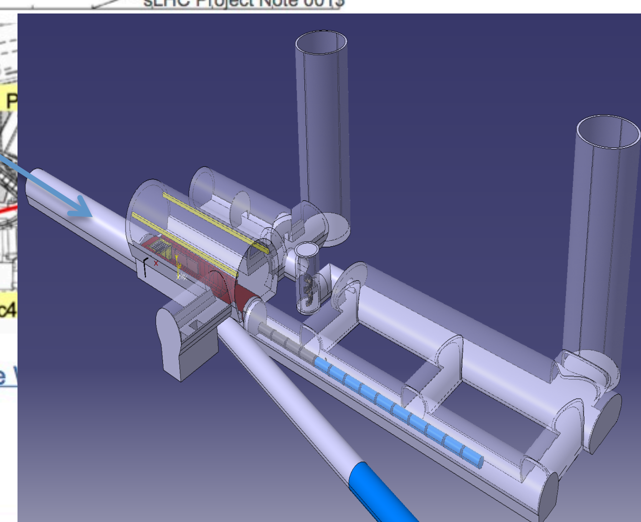






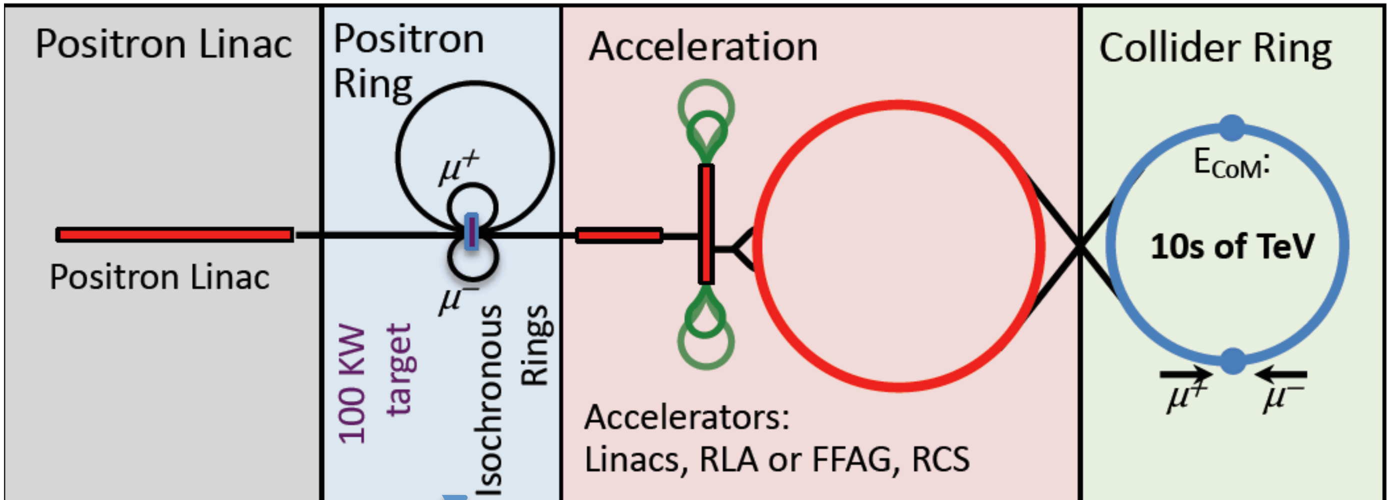
M. Benedikt, LHC Performance

CERN-AB-2007-061

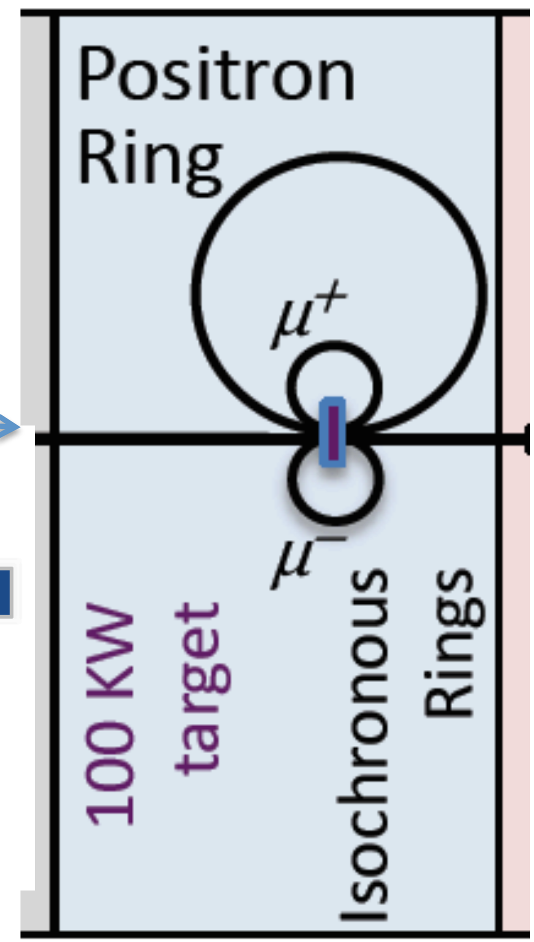


Alternatives: The LEMMA Scheme

LEMMA scheme (INFN)
P. Raimondi et al.

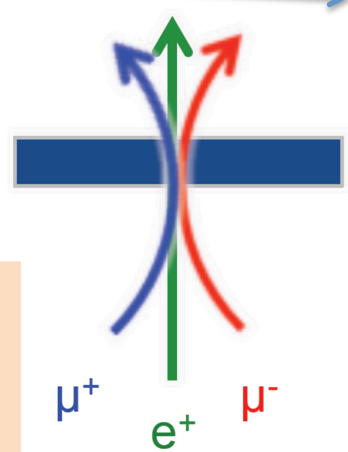


Note: New proposal by C. Curatolo and L. Serafini needs to be looked at
- Uses Bethe-Heitler production with electrons



45 GeV positrons to produce muon pairs
Accumulate muons from several passages

$$e^+e^- \rightarrow \mu^+\mu^-$$



Excellent idea, but nature is cruel
Detailed estimates of fundamental limits show that we require a very large positron bunch charge to reach the same luminosity as the proton-based scheme
$\Rightarrow$ **Need some game changing invention**

European Accelerator R&D Roadmap

CERN Council charged Laboratory Directors Group (LDG) to develop Roadmap

- reviewed by SPC
- agreed by Council December 2021

CERN Council charged LDG to develop implementation plan by March 2022

Roadmap identifies muon collider challenges and two R&D scenarios to address them

- An **aspirational scenario**
- A **minimal scenario**

Scenario	FTEy	kCHF
Aspirational	445.9	11,875
Minimal	193	2,445

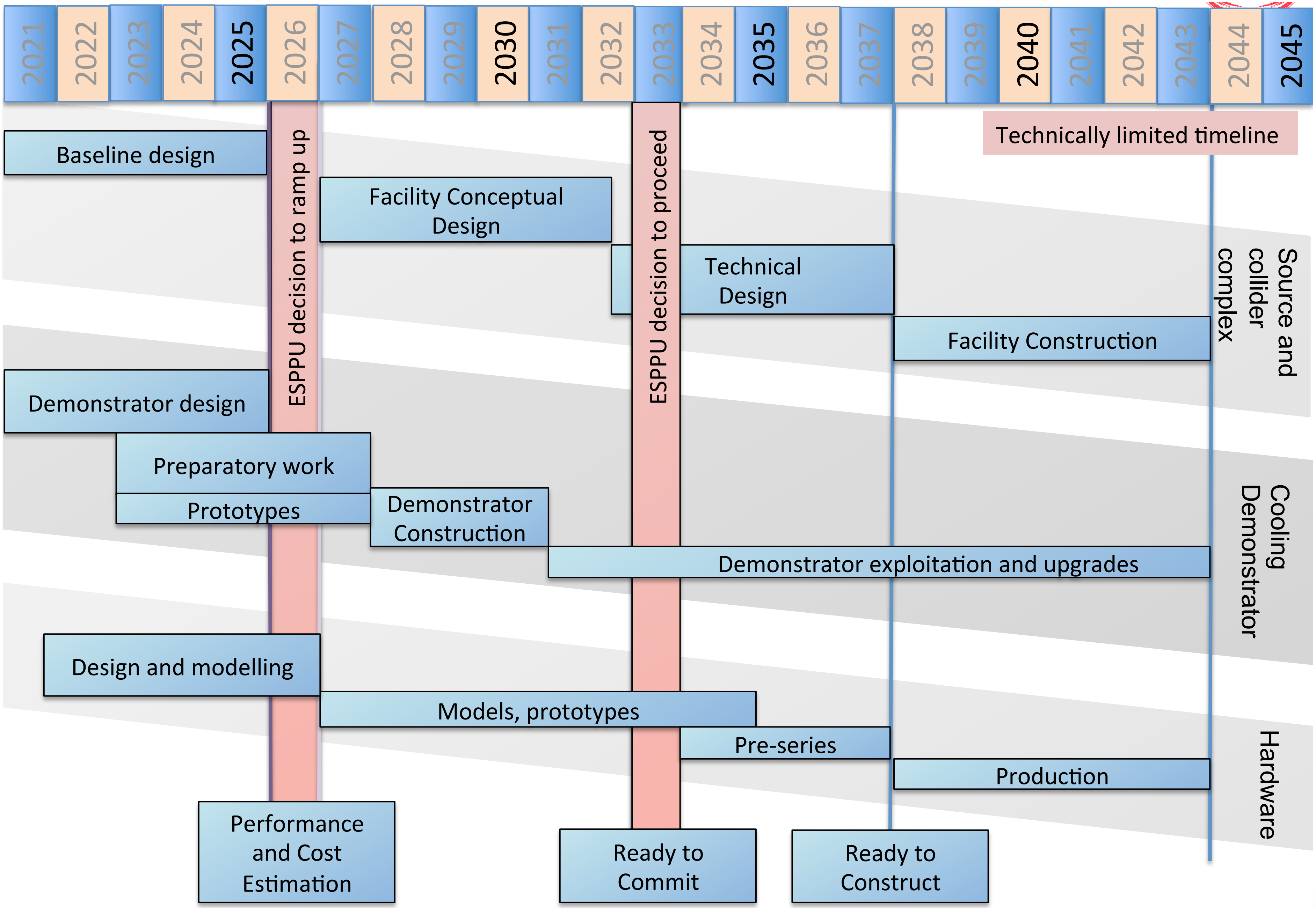
http://arxiv.org/abs/2201.07895

Label	Begin	End	Description	Aspirational [FTEy]	Aspirational [kCHF]	Minimal [FTEy]	Minimal [kCHF]
MC.SITE	2021	2025	Site and layout	15.5	300	13.5	300
MC.NF	2022	2026	Neutrino flux mitigation system	22.5	250	0	0
MC.MDI	2021	2025	Machine-detector interface	15	0	15	0
MC.ACC.CR	2022	2025	Collider ring	10	0	10	0
MC.ACC.HE	2022	2025	High-energy complex	11	0	7.5	0
MC.ACC.MC	2021	2025	Muon cooling systems	47	0	22	0
MC.ACC.P	2022	2026	Proton complex	26	0	3.5	0
MC.ACC.COLL	2022	2025	Collective effects across complex	18.2	0	18.2	0
MC.ACC.ALT	2022	2025	High-energy alternatives	11.7	0	0	0
MC.HFM.HE	2022	2025	High-field magnets	6.5	0	6.5	0
MC.HFM.SOL	2022	2026	High-field solenoids	76	2700	29	0
MC.FR	2021	2026	Fast-ramping magnet system	27.5	1020	22.5	520
MC.RF.HE	2021	2026	High Energy complex RF	10.6	0	7.6	0
MC.RF.MC	2022	2026	Muon cooling RF	13.6	0	7	0
MC.RF.TS	2024	2026	RF test stand + test cavities	10	3300	0	0
MC.MOD	2022	2026	Muon cooling test module	17.7	400	4.9	100
MC.DEM	2022	2026	Cooling demonstrator design	34.1	1250	3.8	250
MC.TAR	2022	2026	Target system	60	1405	9	25
MC.INT	2022	2026	Coordination and integration	13	1250	13	1250
			Sum	445.9	11875	193	2445

Table 5.5: The resource requirements for the two scenarios. The personnel estimate is given in full-time equivalent years and the material in kCHF. It should be noted that the personnel contains a significant number of PhD students. Material budgets do not include budget for travel, personal IT equipment and similar costs. Colours are included for comparison with the resource profile Fig. 5.7.

Aspirational scenario = 10 years of MAP (up to 45 FTE)

Aspirational Timeline



International Muon Collider Collaboration

Memorandum on Cooperation for the Muon Collider (MC) Study

THE INSTITUTES, LABORATORIES, UNIVERSITIES AND FUNDING AGENCIES AND OTHER SIGNATORIES OF THIS MEMORANDUM ON COOPERATION AND CERN AS THE HOST ORGANIZATION ("the Participants")

CERN is the initial host organization for the MC Study.
International collaboration (Iowa University the first US partner)

- [..] the main emphasis of the MC Study shall be to establish whether the investment into a full Conceptual Design Report ("CDR") and demonstrator for a muon collider is scientifically justified. [..]
- In particular, the MC Study shall focus on the high-energy frontier and consider options with a centre-of-mass energy of 3 TeV and of 10 TeV or more. The 10+ TeV option is the reason to study muon colliders, 3 TeV option might be initial energy step with technologies available in 10-20 years
- Potential synergies with other projects shall be explored and used where beneficial to the MC Study. This would include neutrino facilities and potentially higgs factories

muon.collider.secretariat@cern.ch

Conclusion

- Muon collider is unique opportunity for high-energy, high-luminosity lepton collider

- Two different options considered
  - goal is 10+ TeV
  - potential 3 TeV intermediate stage

- Not as mature as ILC or CLIC
  - have to address **important R&D** items
  - but **no showstopper** identified, feasibility is addressed
  - see the (sometimes stony) path forward
  - No inventions needed

- Aim to establish solid basis for performance claim and cost and power estimates

- Aim at **maturity level** to make **informed choices by the next ESPPU** and other strategy processes

- An important opportunity that we should not miss
  - http://muoncollider.web.cern.ch

Many thanks to the Muon Beam Panel, the collaboration, the MAP study, the MICE collaboration, and many others

Reserve

Q&A

- Why no 30 TeV design?
  - No fundamental reason known why not
  - Probably more costly and power consuming than CLIC at 3 TeV
  - Try to focus on what is of importance for physics and what can be committed to in the near future
  - Will make 10 TeV design and then review (neutrino radiation, magnets, …)

- Luminosity at 30 TeV
  - need design of collider and final accelerator ring to know if 90 ab^{-1} can be obtained
  - assuming constant luminosity after 10 TeV is safe assumption based on conservative scaling (e.g. final focus magnets become weaker), only neutrino radiation is not guaranteed

- Cooling techniques
  - In principle a matter of performance and cost, not go or no-go issue
  - final cooling solenoid should be pushed to the limit
  - operation of realistic cells with integrated RF, magnets, absorbers, cooling, vacuum, alignment, instrumentation, …
  - intensity dependent effects (might need proton beam), e.g. absorber, windows, RF, …
  - low emittance operation

- Collider ring losses are O(500 W/m), i.e. 2 x 2 x 10^9 muons/m/s
  - Radiation in magnets will be tuned to be acceptable (need O(30 mm W shielding)

Q&A

- Earliest time for a multi-TeV muon collider is 2044
  - mostly technically limited
  - only exceptional effort could make it faster “put a man to the moon”-like

- What are the technical bottlenecks that drive the schedule?
  - Magnets
  - The cooling scheme is unique has to be developed and optimised. Engineering culture needs to be developed.

- Why is the muon collider still 20 years in the future?
  - In the past few years the muon collider has had limited resources.
  - Experience indicates that one needs to spent 500 MCHF on development before one can launch into the project

- What can we learn from MICE?
  - Strong, laboratory-driven organisation is essential. The formal procedures of big laboratories can pay off.

- Does the accelerator community need more early career physicists?
  - At least in Europe, yes. Requires funds to hire them.

Q&A

- Are their real efforts on synergy between the muon collider and neutrino facilities?
  - This is slowly building up. E.g. will check if a test facility based on PS be used for NuStorm.
  - You will have to tell us what to do.
- Does the R&D path to a ~10 TeV muon collider require any technological leaps?
  - We do have solutions for the collider parts but need R&D. We see a path forward, e.g. stress-managed magnets. We do not need to hope for a miracle.
- What are the highest priority items?
  - Best to refer to the Roadmap.
- Does the R&D for a higgs and a multi-TeV collider differ and does it makes sense to focus on one?
  - There is important overlap. The higgs factory does not need the final cooling and the high-energy acceleration but has a challenging collider ring. A muon collider higgs factory is a good thing but with strong competition at this moment. A multi-TeV muon collider is a unique opportunity.
- Which muon collider technologies are of general use?
  - The whole magnet work, in particular the solenoids (which other colliders do not develop) and the fast-ramping magnets with energy recovery.
  - Target development is useful for other applications (e.g. neutron spallation source)

Q&A

- What would the ideal international muon collider collaboration look like?
  - Not sure what the ideal one would look like. We have an international collaboration hosted by CERN. You are welcome to join. The host role can change as things evolve.

- Luminosity

- Detector studies
  - support them

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- An **International Collaboration Board (ICB)** oversees the the MC study and channels contributions from the participants.

- An **International Advisory Committee** will be established whose mandate is to review the scientific and technical progress of the Study typically on an annual basis and to submit recommendations to the ICB.

- A **MC Study Leader** who organises and guides the study, establishes collaborations, ensures coherent communications, coordinates the resources and organises workshops, conferences and meetings where relevant. He or she will be appointed by the ICB and guided by its decisions, and will act under the authority of the head of the host organization

Collaboration Scope

- At the date of conclusion of this Memorandum it is envisaged that the main emphasis of the MC Study shall be to establish whether the investment into a full Conceptual Design Report ("CDR") and demonstrator for a muon collider is scientifically justified. The MC Study shall provide a baseline concept for a muon collider, well-supported performance expectations and assess the associated key risks as well as the cost and electricity consumption drivers. It shall also identify an R&D path to demonstrate the feasibility of the collider and support its performance claims.

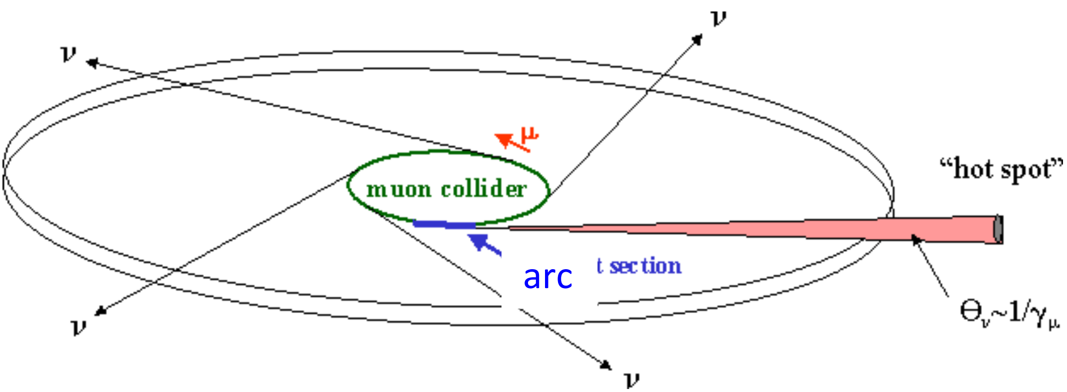
- In particular, the MC Study shall focus on the high-energy frontier and consider options with a centre-of-mass energy of 3 TeV and of 10 TeV or more.

The 10+ TeV option is the reason to study muon colliders
a 3 TeV option might be initial energy step with technologies available in 10-20 years

- Potential synergies with other projects shall be explored and used where beneficial to the MC Study.

This would include neutrino facilities and potentially higgs factories

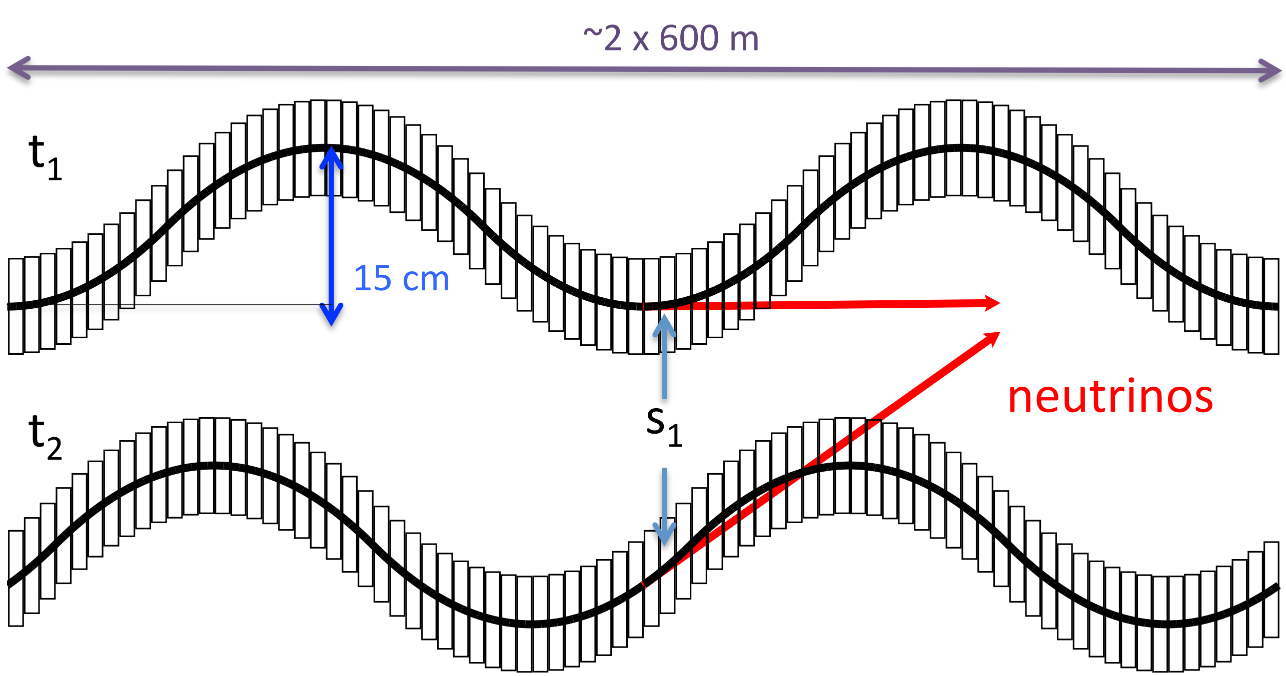
Neutrino Flux Mitigation



Dense neutrino flux can be issue at high energies
Want to remain similar to LHC level

- Arcs in 3 TeV, are about OK 200 m deep tunnel is about OK
- 10+ TeV is close to legal limit

Proposed solution: based on idea of Mokhov, Ginneken to move beam in aperture
our approach: move collider ring components, e.g. vertical bending with 1% of main field



Opening angle ± 1 mradian

14 TeV, in 200 m deep tunnel comparable to LHC case

Need to study mover system, magnet, connections and impact on beam

Working on different approaches for experimental insertion

Muon Collider Luminosity Scaling

International MUON Collider Collaboration

Fundamental limitation
Assumes no emittance growth after source and no technical limitation
Applies to MAP and LEMMA scheme

$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon \epsilon_L} f_r N_0 \gamma$$

Muon current for MAP scheme 10^{13} s^{-1}

LEMMA scheme O(0.7 mJ) positrons lost per produced muon pair
⇒ 100 MW loss yield 1.4 x 10^{11} s^{-1} muons (proton case: 1 x 10^{13} s^{-1})
⇒ Need 70 times denser beam
⇒ Lose 1.4 10^{16} positrons per second
⇒ Pass 1.4 10^{18} positrons through target per second

Assume 3mm thick Be target
⇒ Emittance growth per muon beam passage through target (optimum case)
⇒ Need 100 bunches with 3 x 10^{15} positrons (=22 MJ) to pass through target to obtain required muon beam emittance
⇒ Positron beam energy 2 GJ/burst, 5 burst per second
⇒ Energy deposition in target 60 kJ per pulse (minimum ionisation) 4.5 MK temperature rise per bunch (linear approximation)
⇒ Extremely challenging, not sure even a fluid target can do this

Some Comments

F. Zimmermann 2018 J. Phys.: Conf. Ser.1067 022017 claims

$$L \approx f_{\rm rev} \dot{N}_\mu \frac{\dot{N}_\mu}{\varepsilon_N} \frac{1}{3^6} \gamma \tau^2 \frac{1}{4\pi\beta^*}$$

$$= \frac{1}{3^6} \left\{ \left(\frac{eF_{\rm dip}}{2\pi m_\mu} \right)^3 \frac{\tau_0^2}{4\pi c^2} \right\} \left[B^3 C^2 \right] \left[\dot{N}_\mu \frac{\dot{N}_\mu}{\varepsilon_N} \right] \frac{1}{\beta^*}$$

$$\mathcal{L} \propto \frac{(f_r N)^2}{\epsilon}$$

The paper assumes that muons can be stacked but ignores the associated emittance growth

This is wrong, with these assumption LEMMA would be viable

the LEMMA scheme

New proposal by C. Curatolo and L. Serafini needs to be looked at uses Bethe Heitler production with electrons

scheme	p-γ	G.-F. μ	e^+	G.-F. e^+
base	LHC/FCC-hh		FCC-ee	FCC
rate $\dot{N}_\mu$ [GHz]	1	400	0.003	100
μ/pulse [10^4]	0.01	4	0.2	6,000
p. spacing [ns]	100	100	15	15
energy [GeV]	2.5	0.1	22	22
rms en. spread	3%	10%	10%	10%
n. emit. [μm]	7	2000	0.04	0.04
$\dot{N}_\mu/\varepsilon_N$ [10^{15} m^{-1}s^{-1}]	0.1	0.2	0.1	3,000

at 14 TeV:
9 GW beam power

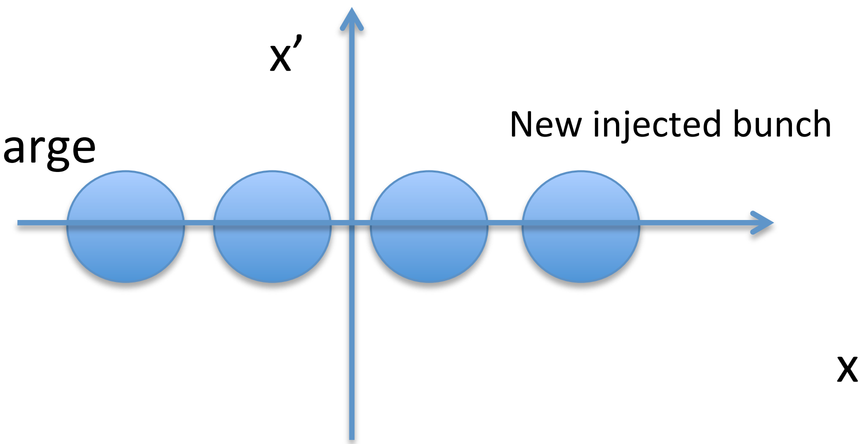
even 30 times more beam particles

Note: Stacking

$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon \epsilon_L} f_r N_0 \gamma$$

stacking in longitudinal plane does not increase luminosity

bunch length and beta-function increase with the charge



Stacking in transverse plane can help because

$$\epsilon = \sqrt{\epsilon_x \epsilon_y}$$

stacking m^2 bunches leads to

$$N = m^2 N_1 \qquad \epsilon = m \epsilon_1$$

and the luminosity scales as

$$\frac{N}{\epsilon} = m \frac{N_1}{\epsilon_1}$$

$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N}{\epsilon \epsilon_L} f_r N \gamma$$

$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta m \frac{N_0}{\epsilon_0 \epsilon_{L,0}} f_{r,0} N_0 \gamma$$

$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \sqrt{f_{r,0} \tau \gamma} \frac{N_0}{\epsilon_0 \epsilon_{L,0}} f_{r,0} N_0 \gamma$$

Memorandum of Cooperation

CERN is initially hosting the study

- International collaboration board (ICB) representing all partners
  - elect chair and study leader
  - can invite other partners to discuss but not vote (to include institutes that cannot sign yet)
- Study leader
- Advisory committee reporting to ICB

Addenda to describe actual contribution of partners

Contact: alexia.augier@cern.ch

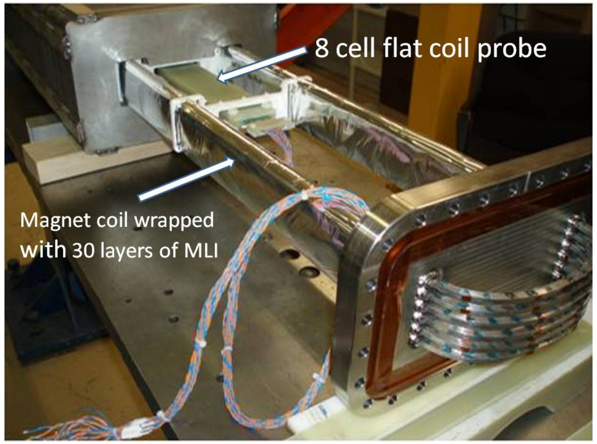
Technology Challenges and Status

International
MUON Collider
Collaboration

FNAL
290 T/s
HTS

Need to push in field and speed

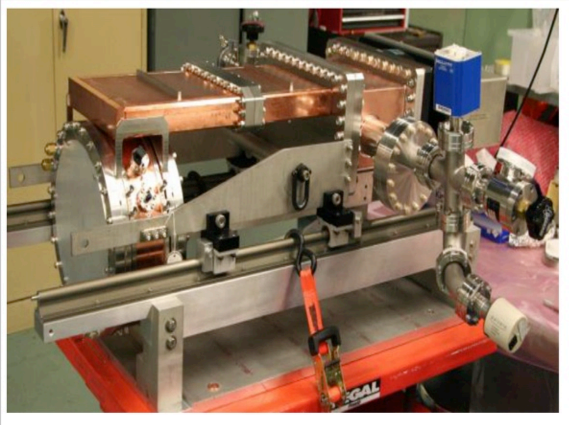
Test of **fast-ramping normal-conducting magnet** design

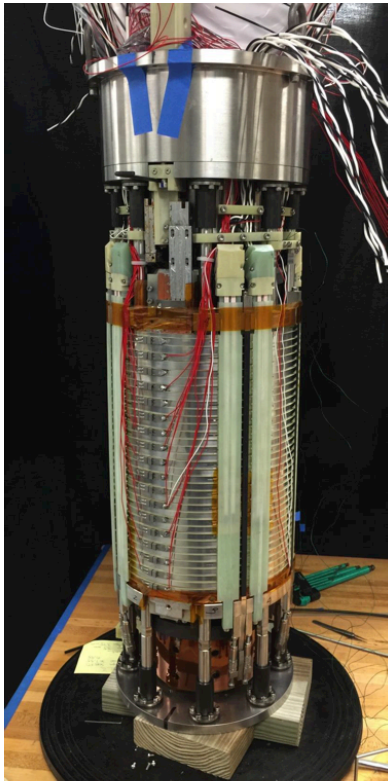


MuCool: >50 MV/m in 5 T field

Two solutions

- Copper cavities filled with hydrogen
- Be end caps

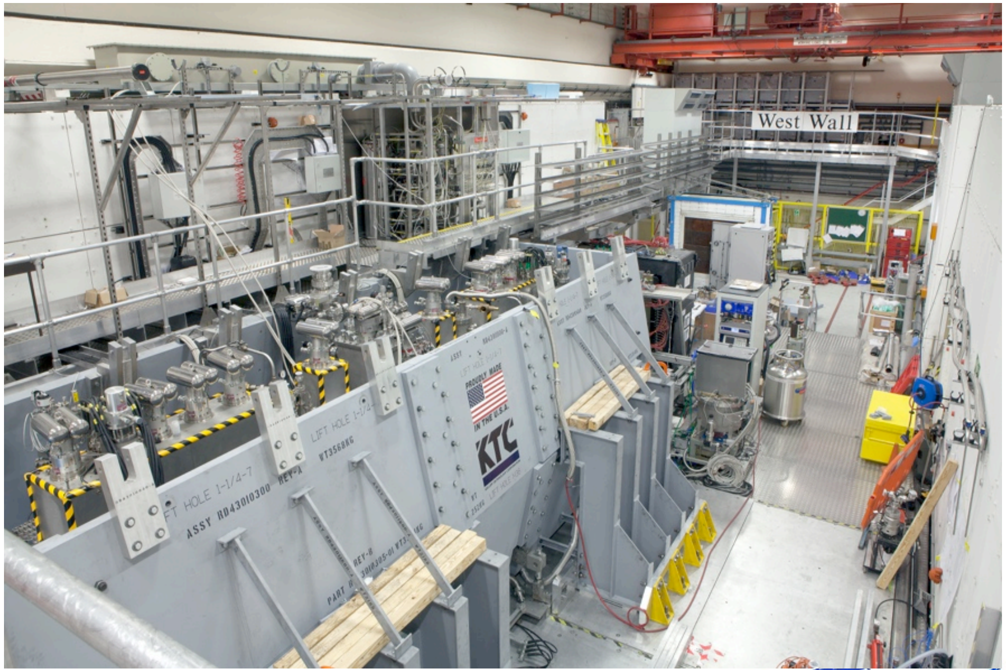




NHFML
32 T solenoid
with HTS

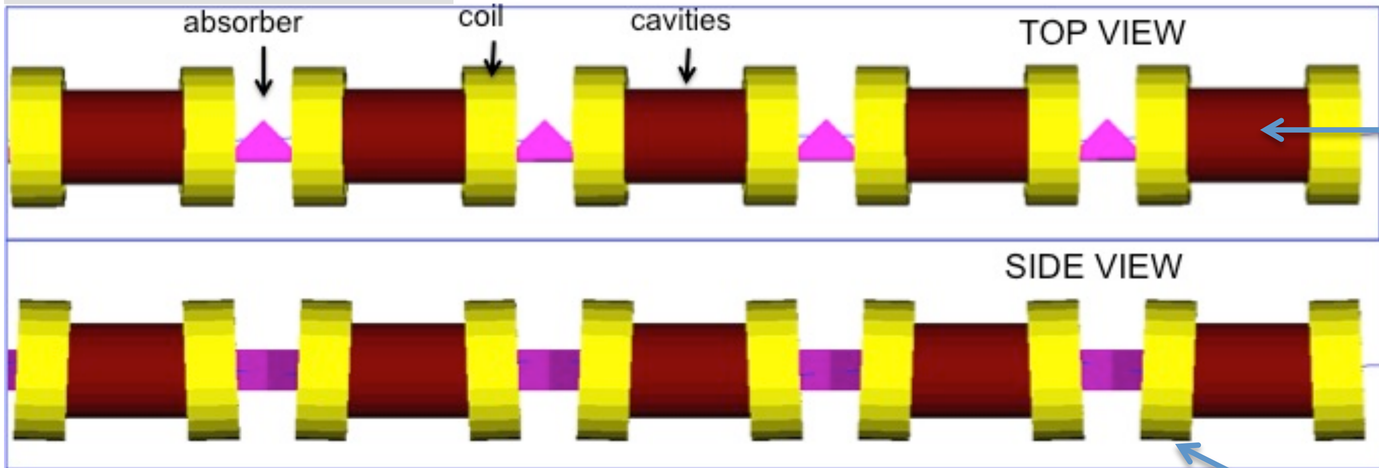
Next goal 40 T probably 60 T is possible

MICE (UK) Muon cooling principle



Cooling Concept

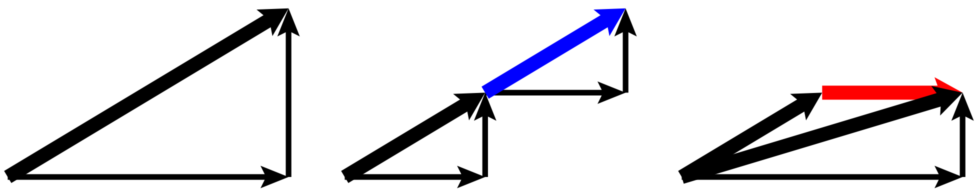
MAP collaboration



Limit muon decay, cavities with **high gradient in a magnetic field**
tests much better than design values but need to develop

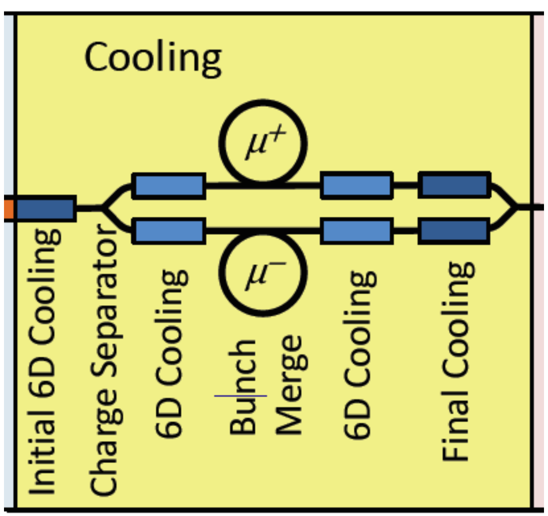
Compact integration to minimise muon loss

Minimise betafunction with **strong solenoids**



energy loss

re-acceleration



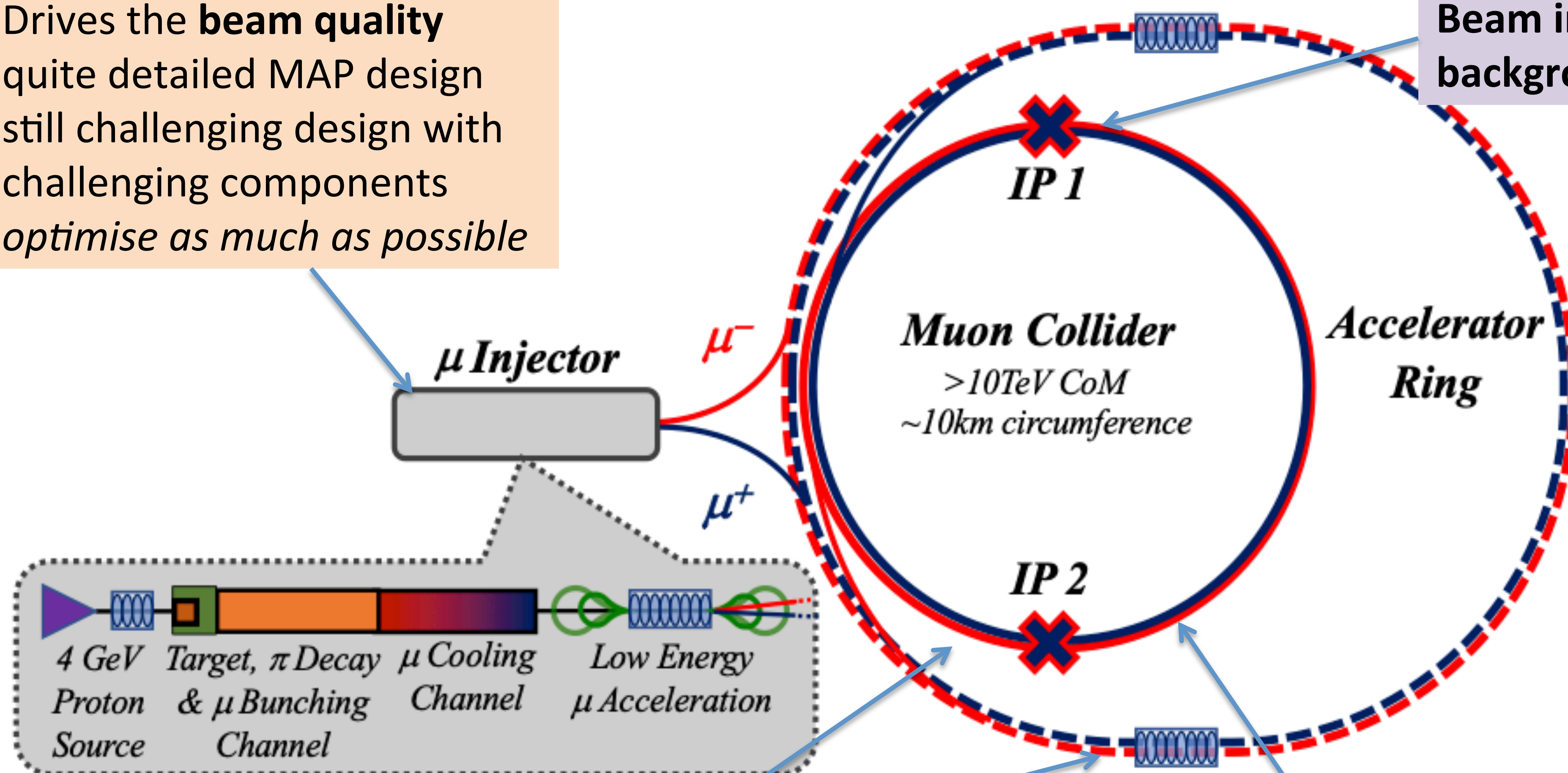
Need to **optimise lattice design** to gain factor 2 in emittance, integrating demonstrated better hardware performances

This is the **unique** and **novel** system of the muon collider
Will need a **test facility**
The principle has been demonstrated in MICE

Key Challenges

Drives the **beam quality**
quite detailed MAP design
still challenging design with
challenging components
optimise as much as possible

Beam induced background



Dense neutrino flux
mitigated by mover
system and site selection

Cost and **power** consumption drivers, limit energy reach
e.g. 30 km accelerator for 10/14 TeV, 10/14 km collider ring
Also impacts **beam quality**

Example Cell Designs

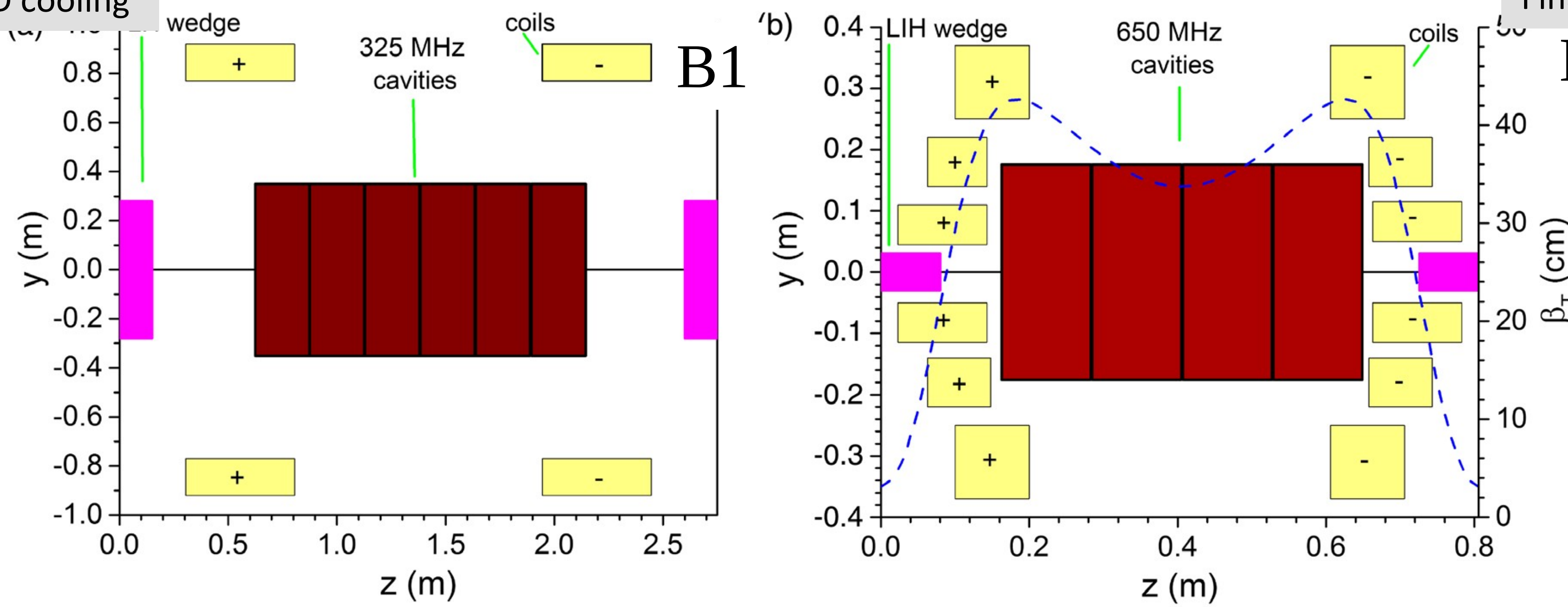
Main 6D-cooling has many magnets and needs **tight integration** with RF and absorbers

Initial 6D cooling

Final 6D cooling

2.2 T

13.6 T



Are already aware of slightly violated space constraints

- maybe cool copper can help both gradient, space and peak power

Alignment has to be integrated (e.g. additional bellows)

Beam operation is important, e.g. beam position on absorber wedge, diagnostics integration, …

Timeline

Initial design phase 2021-2025

Establish whether investment into full CDR and demonstrator is scientifically justified.

Provide a baseline concept, well-supported performance expectations and assess the associated key risks as well as cost and power consumption drivers.

Identify an R&D path toward the collider, considering High-field Magnet and RF Roadmap results.

Design phase 2026-

Develop concept and technology to be ready to commit

Verify performance of all key components. In particular, build cooling cell string and test with beam. Build and test magnet models and RF components. Start building industrial base for production. Develop site and infrastructure. Determine cost, power, construction schedule. Optimise design.

Technical design phase

Prepare approval and project implementation

Prepare industrial production of components, e.g. build magnet prototypes and preseries with industry. Prepare site for construction. Refine cost, power and construction schedule.

Strategy decision (2026)

Define performance goals and timeline for muon collider

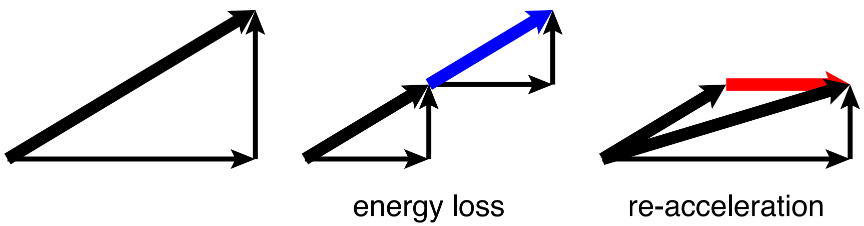
Potentially ramp up of muon collider effort

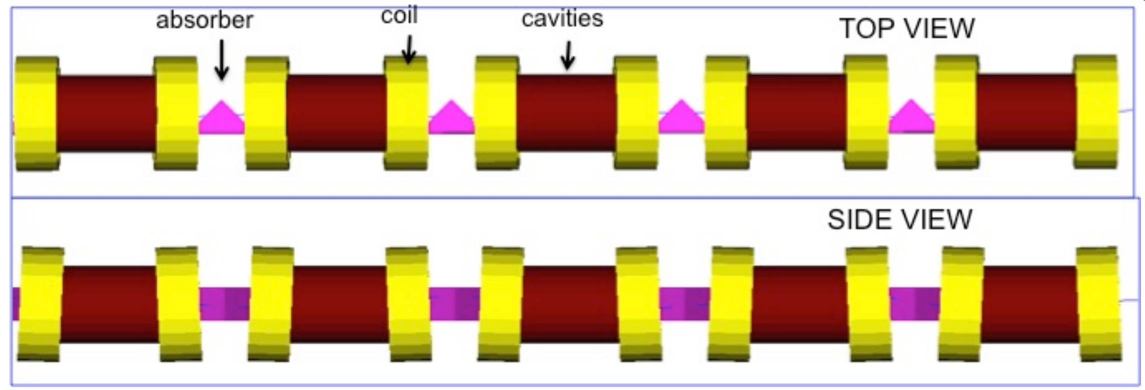
Decision to move to technical design

Pre-commitment to project

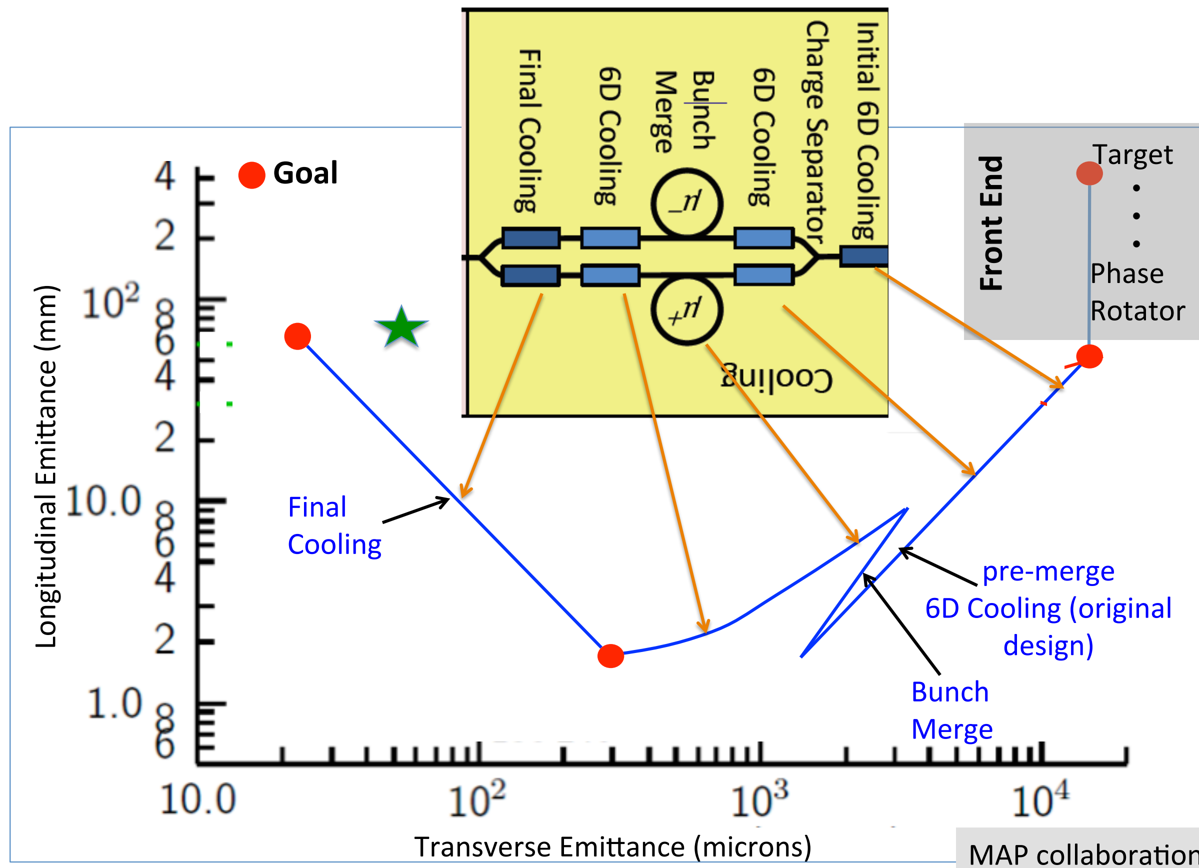
Project Approval

Proton-driven Muon Collider Concept



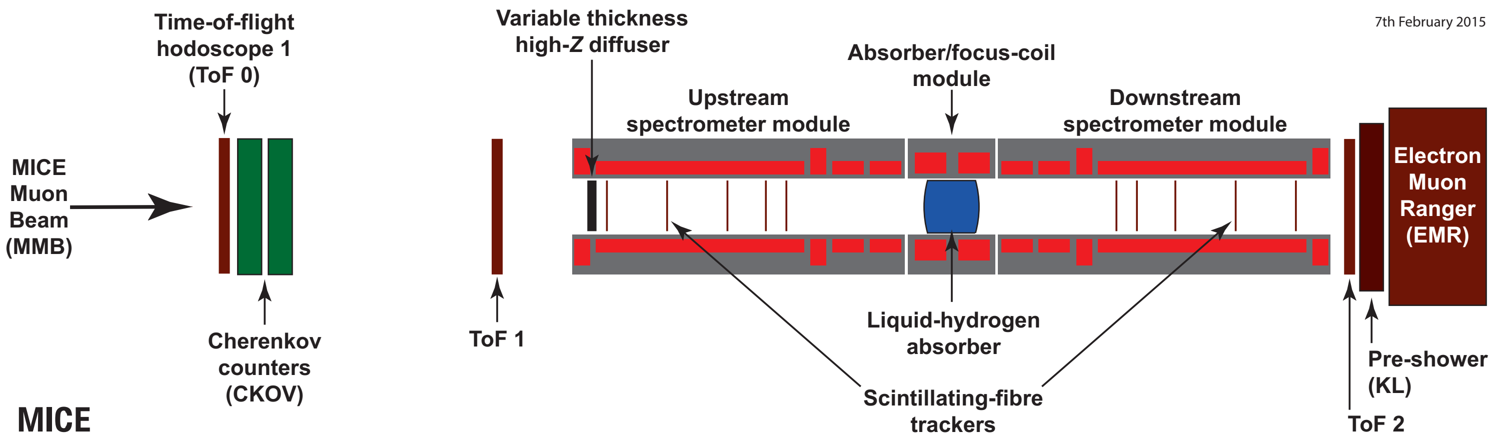


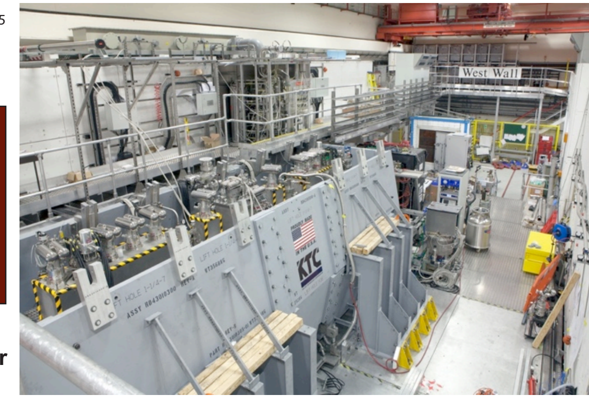
Existing projects of 40 T solenoids at EMFL, NHMFL



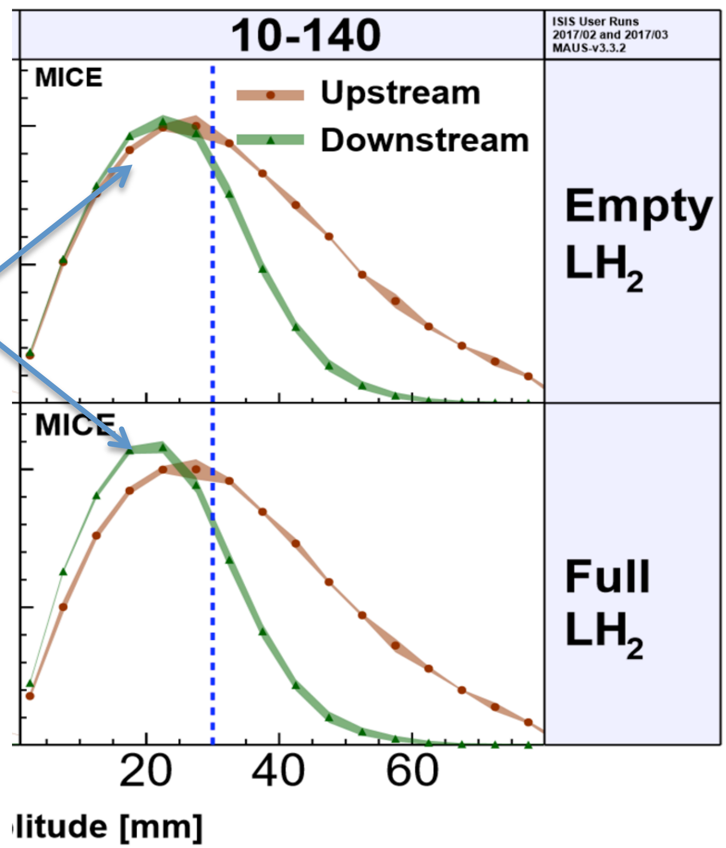
MAP collaboration

MICE (in the UK)





More particles at smaller amplitude after absorber is put in place



Nature volume 578, pages 53-59 (2020)

Principle of ionisation cooling has been demonstrated

More complete experiment with higher statistics, more than one stage required

Integration of magnets, RF, absorbers, vacuum is engineering challenge